DESIGN STUDY OF THE PROPOSED 12SLOT-14POLE FIELD EXCITATION FLUX SWITCHING MACHINE (FEFSM) FOR HYBRID ELECTRIC VEHICLES

NAZIRA BINTI YUNUS

A project report submitted in partial
fulfillment of the requirement for the award of
the Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JULY 2014

ACKNOWLEDGEMENT

Firstly, I would like to take this opportunity to thank the Almighty Allah for His mercy,His grace and kindness in my life as a slave and His blessing given to me for the completion my study in of Universiti Teknologi Tun Hussein Onn, Johor,Malaysia.

Secondly, I would like to record my gratitude to Dr Erwan Bin Sulaiman for his supervision, advice, and guidance from the very early stage of this research as well as giving me extraordinary experiences throughout my research work. His truly scientist intuition has made him as a constant oasis of ideas and passions in science, which exceptionally inspire and enrich my growth as a student, a researcher and a scientist want to be. I'm also indebted to him more than he knows.

Furthermore, my family deserves special mention for their inseparable support and prayers. I would like to thank my husband, Mr Ahmad Tarmizi bin Abd Rahman, whose dedication, love and persistent confidence in me, has taken the load off my shoulder. Thanks also to our kids Ahmad Aleef Tamimi, Ahmad Afif Taufiq, Ahmad Arif Thaqif and Fatimah Athiyyah who brightened the lives of our family. I would also like to thank my parents and family members for their moral support towards the completion of my study. A sincere thank to my father Mr Yunus Bin Othman who teach the fundamental of my life, showing me the right path, and continous prayer since I was a child, and also to my mother, Mrs Fatimah Binti Ngah which is the one who sincerely raised me with her caring and gentle mother's love.

Finally, I would like to thank everybody who was important to the successful realization of this thesis, as well as expressing my apology that I could not mention personally one by one.

ABSTRACT

A new structure of field excitation flux switching motor (FEFSM) as an alternative candidate of non-Permanent Magnet (PM) machine for HEV drives is presented in this thesis. Design principles and initial performances of the proposed motor with 12 stator slots and 14 rotor pole are demonstrated. Initially, the coil arrangement tests are examined to validate the operating principle of the motor and to certify the zero rotor position. Furthermore, the profile of flux linkage,cogging torque, torque versus Ja at various Je characteristics and torque versus power characteristics are observed and analyzed based on 2D-finite element analysis (FEA). The improvement design is done by using the "deterministic optimization method" to achieve the restriction and spesification target compared to Interior Permenant Magnet Synchronous Machines (IPMSM) that used in HEV drives. "The results obtained show that proposed 12S-14P FEFSM achieved the target performance for maximum power, maximum torque density, maximum power density and machine weight, while the maximum torque is not achieved as a target. Therefore, by further design modification and optimization it is expected that the low cost motor will successfully achieved the target performances.

ABSTRAK

Satu struktur baru mesin iaitu "*Field Excitation Flux Switching motor"* (FEFSM) dibentangkan di dalam tesis ini sebagai alternatif mesin bukan Magnet Tetap (PM) untuk pemacu "*Hybrid Electric Vehicle"* (HEV). Prinsip reka bentuk dan persembahan awal motor yang dicadangkan dengan 12 slot pemegun dan 14 kutub pemutar ditunjukkan. Pada awalnya, ujian susunan gegelung diperiksa untuk mengesahkan prinsip operasi motor dan kedudukan sifar stator. Tambahan pula, profil rangkaian fluks, cogging tork, ciri-ciri tork berbanding Ja pada pelbagai Je dan ciri-ciri tork berbanding kuasa dipatuhi dan dianalisis berdasarkan analisis unsur terhingga 2D (FEA). Reka bentuk penambahbaikan dilakukan dengan menggunakan "*deterministic optimization method*" untuk mencapai sasaran had dan spesifikasi, yang diukuran berbanding *"Interior Permenant Magnet Synchronous Machine*" (IPMSM) yang digunakan pada pemacu HEV. "Keputusan yang diperolehi menunjukkan bahawa cadangan 12S-14P FEFSM mencapai prestasi sasaran untuk kuasa maksimum, ketumpatan tork maksimum, ketumpatan kuasa maksimum dan berat mesin, manakala tork maksimum tidak dicapai seperti yang disasarkan. Oleh itu, dengan pengubahsuaian reka bentuk dan pengoptimuman lagi adalah dijangka bahawa motor yang berkos rendah akan berjaya mencapai sasaran yang diharapkan.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

LIST OF SIMBOL

PM	Permanent Magnet
FEFSSM	Field Excitation Flux Switching Synchronous Machine
FEFSM	Field Excitation Flux Switching Machine
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
IM	Induction Machines
SRM	Switch Reluctance Machine
PMBL	Permanent Magnet Brushless
DC	Direct Current
IPMSM	Interior Permanent Magnet Synchronous Machines
MRIC	Mineral Resource Information Center
FEC	Field Excitation Coil
AC	Armature Coil
DSPM	Doubly Salient Permanent Magnet
FRM	Flux Reversal Machine
HEFSM	Hybrid Excitation Flux Switching Machine
PMFSM	Permanent Magnet Flux Switching Machine

J_e	Current Density of Excitation Coil
J_a	Current Density of Armature Coil
S_e	Area of Excitation Coil
S_a	Area of Armature Coil

CHAPTER 1

INTRODUCTION

1.1 Research Background

A new structure of field excitation flux switching motor (FEFSM) as an alternative candidate of non-Permanent Magnet (PM) machine for HEV drives is proposed for this project. This project presents the 12Slot-14Pole field-excitation flux switching synchronous machine (FEFSSM) with all active parts i.e. field excitation coil (FEC) and armature coil are located on the stator, applied for hybrid electric vehicles (HEVs). The rotor part consists of single piece iron makes it more robust and becoming more suitable to apply for high speed motor drive system application coupled with reduction gear [**1**]. This project deals with design and improvement of the proposed 12S-14P inner rotor field excitation flux switching motor(FEFSM) for electric vehicle applications. The design restriction and target specifications of the proposed machine for HEV compare with conventional IPMSM.

Hybrid electric vehicles (HEVs), via combination of an internal combustion engine (ICE) and one or more electric machines, are widely measured as the most promising solution for clean vehicles. There are four major types of electric machine that are feasible for HEVs, namely, DC machines, induction machines (IM), switch reluctance machines (SRM), and permanent magnet (PM) brushless (PMBL) machines. DC machines are used to be widely accepted for EVs and HEVs because of their advantage of simple control of the orthogonal disposition of field and armature mmf. However, the principle problem of dc drives, due to their commutators and brushes, makes them less reliable and unsuitable for a maintenance-free operation [**2**] [**3**] [**4**].

In other circumstances, induction machines are a widely accepted brushless drive for the electric propulsion of HEVs, owing to their reliability, ruggedness, low maintenance, low cost, and ability to operate in hostile environments. However, the presence of a breakdown torque limits its extended constant-power operation. At the critical speed, the breakdown torque is reached. Generally, for a conventional IM, the critical speed is around two times the synchronous one. Any attempt to operate the motor at the maximum current beyond this speed will stall the motor. Moreover, efficiency at a high speed range may suffer in addition to the fact that IMs efficiency is inherently lower than that of PM motors, due to the absence of rotor winding and rotor copper losses .

Meanwhile, SRM have been recognized to have a considerable potential for HEVs. They have the definite advantages of simple construction, low cost, and outstanding torque-speed characteristics. Although they possess simplicity in construction, their design and control are difficult and subtle. In addition, they usually exhibit acoustic-noise problems [**5**]. Finally, PMBL machines are becoming more and more attractive and can directly compete with the induction machines for HEVs. The definite advantages of PMBL machines are their inherently high efficiency, high power density, and high reliability. The key problem is their relatively high cost due to PM materials. In recent years, the class of PM BL drives has been expanded to embrace those with hybrid field excitations [**6**].

One example of successfully developed electric machines for HEVs is Interior Permanent Magnet Synchronous Machines (IPMSMs). This machine consists of large volume of PM as their main flux sources located in the rotor. The great merit of applying PM is to reduce the weight of the machine so that it can reduce the machine weight, hence increases the torque and power density of the machine [**7**]. This can be proved by the historical progress in the power density of main traction motor installed on Toyota HEVs, where the power density of each motor employed in Lexus RX400h'05 and

GS450h’06 have been improved approximately five times and more, respectively, compared to that installed on Prius’97 .

On the other hand, although the torque density of each motor has been changing hardly, a reduction gear has enabled to raise up the axle torque necessary for propelling the large vehicles such as RX400h and GS450h. Therefore, as one of the effective strategies for increasing the motor power density, the technological tendency to employ the combination of a high speed machine and a reduction gear would be accelerated.

From this trend, IPMSM design tends to be difficult because all PM are placed on the rotor part and hence, to ensure the mechanical strength of rotor relies on the number of bridges and rib thickness between PM. Increase in the number of bridges would improve the mechanical strength, but, it would also reduce the maximum torque of the machine due to an increase in flux leakage. In addition, the parameters of the main machine part such as v-shape of PM, air gap slot on the rotor and armature coil slot shape are difficult to optimize.

The major requirements of HEVs electric propulsion, as mentioned in past literature, are summarized as follows:

(i) high instant power and high power density

(ii) high torque at low speed for starting and climbing, as well as high power at high speed for cruising

(iii) very wide speed range, including constant-torque and constant-power regions

(iv) fast torque response

(v) high efficiency over the wide speed and torque ranges

(vi) high efficiency for regenerative braking

(vii) high reliability and robustness for various vehicle operating conditions reasonable cost

1.2 Problem Statement

In other situations, according to the report released by Mineral Resource Information Center (MRIC) associated to Japan Oil and Gas and Metals National Corporation, the increase in annual usage of rare-earth magnet has increased the price of Neodymium (Nd), Dysprosium (Dy) and Terbium (Tb) which are indispensable to provide the rare-earth magnet with high coercivity as the additives. Moreover, a future prospect was shortened such that the production amount of Nd2Fe14B would reach 1,500 tons only in HEV applications by 2012 and the corresponding usage of Dysprosium, 70 tons, would be a serious problem from the viewpoints of cost, security of the rare-earth materials and supply shortage. Therefore, the continuous researches and developments on a new machine with high power density, robust rotor structure for high-speed operation, and with no or less-rare-earth magnet machines would be very important [**8**].

As one alternate solution with high possibility to overcome this problem, a new design of 12Slot-14Pole field-excitation flux switching synchronous machine (FEFSSM) with no permanent magnet is proposed. Both FEC and armature coils are allocated at stator side. The rotor covers of only single piece iron, becoming more robust and more suitable for high speed operation. Although less pole number reduces the supply frequency of inverter, the 12Slot-14Pole machine is selected and proposed in this research because;

(1) it can be considered as the best minimum combination of slot-pole to avoid odd rotor pole numbers such as 6Slot-5Pole and 6Slot-7Pole machines yielding unbalanced pulling force,

(2) to avoid high torque ripples in case of 6Slot-8Pole and 6Slot-4Pole machines, and

(3) to take good balance between rotor and stator pole widths for minimizing inescapable torque pulsation.

1.3 Objectives

The objectives of this research is

i. To design the proposed 12Slot-14Pole inner rotor field excitation flux switching motor for electric vehicle applications.
ii. To analyze performance of the design motor under no load, load, torque, power and torque and power density of 12Slot-14Pole inner rotor field excitation flux switching motor (FEFSM) for electric vehicle applications motor
iii. To improve the performance of initial design of 12Slot-14Pole inner rotor field excitation flux switching motor (FEFSM) for electric vehicle applications.

1.4 Project Scopes

The scope of this project is

i. This project is design by using JMAG Designer version 13.
   JMAG is simulation software for the development and design of electrical devices. JMAG incorporates simulation technology to accurately analyze a wide range of physical phenomenon that includes complicated geometry, various material properties, and the heat and structure at the center of electromagnetic fields. Besides, JMAG is also being used for the development of drive motors for electric vehicles.
ii. The design restriction and target specifications of the proposed machine for HEV compare with conventional IPMSM.

iii. The limit of the current density is set to the maximum of $30A_{rms}/mm^2$ for armature winding (J_a) and $30A/mm^2$ for excitation coil (J_e). The limit of current is set to maximum of 360A for armature winding(I_a) and 50A for excitation coil(I_e).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction To Flux Switching Motor (FSM)

In the middle of 1950s, the first concept of flux switching machine (FSM) was started and published [**9**]. In [**9**], a permanent magnet flux switching machine (PMFSM), i.e. permanent magnet (PM) single-phase limited angle actuator or more well-known as Laws relay, having 4 stator slots and 4 rotor poles was developed, while in [**10**] it was extended to a single phase generator having 4 stator slots, and 4 or 6 rotor poles. Over the last ten years or so, many novel and new FSM topologies have been developed for various applications, ranging from low cost domestic appliances, automotive, wind power, aerospace, and etc.

Generally, the FSMs can be classified into three groups that are permanent magnet flux switching machine (PMFSM), field excitation flux switching machine (FEFSM), and hybrid excitation flux switching machine (HEFSM). Both PMFSM and FEFSM has only PM and field excitation coil (FEC), respectively as their main flux sources, while HEFSM contains both PM and FEC as their main flux sources. Fig. 1 clarifies the general classification of FSMs.

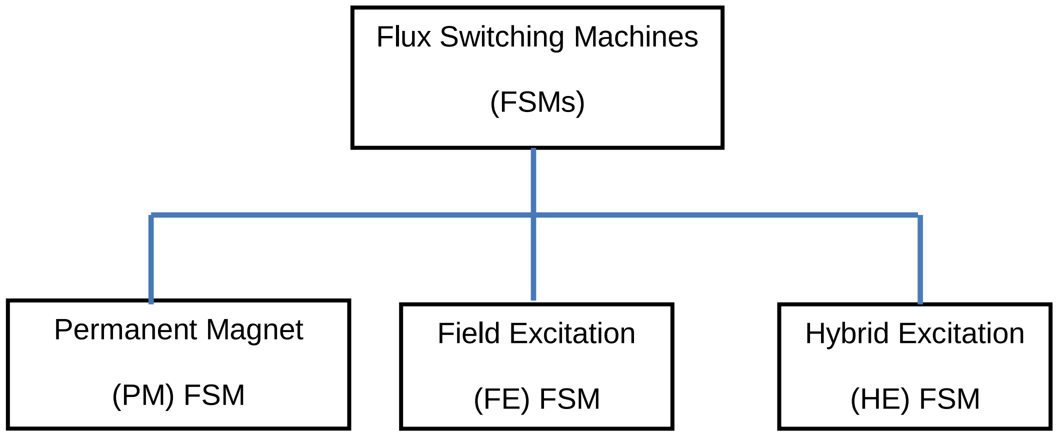

Fig. 2. 1:Classification of Flux Switching Machines

2.2 Permanent Magnet Flux Switching Motor (PMFSM)

The permanent magnet flux-switching machine (PMFSM) has a short history and is a relatively new category of electric machines. The basic model of PMFSM was designated in [**11**][18], where Rauch and Johnson proposed a new type of motor with permanent magnets placed in the stator in order to better control their temperature, and was brought back to the scene [**12**] due to a multitude of reasons, including the limit of permanent magnetic materials and the necessity of sophisticated computer-aided motor design tools. The PMFSM's have been receiving significant attention in the last two decades thanks to the advantages of high power density, mechanical robustness and torque capability. The PMFSM is very similar to the doubly salient permanent magnet (DSPM) machine or to the flux reversal machine (FRM) [**13**], [**14**]. The examples of three-phase PMFSM are illustrated in Fig. 2.2.

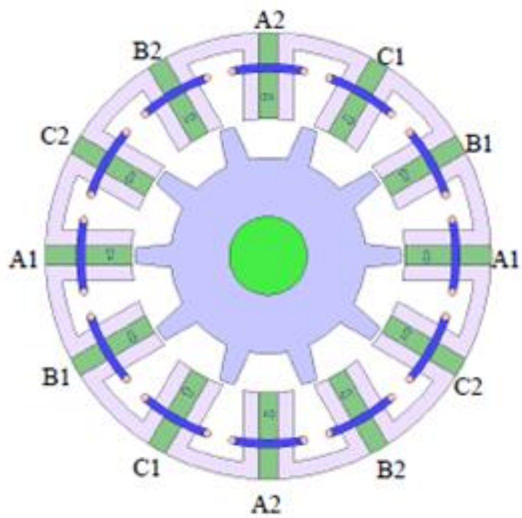

Fig. 2. 2: Examples of 12S-10P PMFSM

In other conditions, Permanent Magnet Flux Switching Machines (PMFSM) has been a popular research topic due to its high power density and robust rotor structure. With both permanent magnets and armature windings situated at the stator and robust single piece rotor similar to that of the switched reluctance machine, the PMFSM have benefits of ease cooling of all active parts such as armature coil and permanent magnets and better suitability for high speed application compared to conventional PM machines [**15**].

The general operating principle of the PMFSM is shown in Fig. 2.3, where the black arrows show the flux line of PM as an example. From the figure, when the relative position of the rotor poles and a particular stator tooth are as in Fig. 2.3(a), the flux-linkage corresponds to one polarity. However, the polarity of the flux-linkage reverses as the relative position of the rotor poles and the stator tooth changes as shown in Fig. 2.3(b), i.e., the flux-linkage switches polarity as the salient pole rotor rotates. In the conventional PMFSM, the stator copper area is significantly reduced since both the PMs and armature coils are housed in the stator with high PM volume employed.

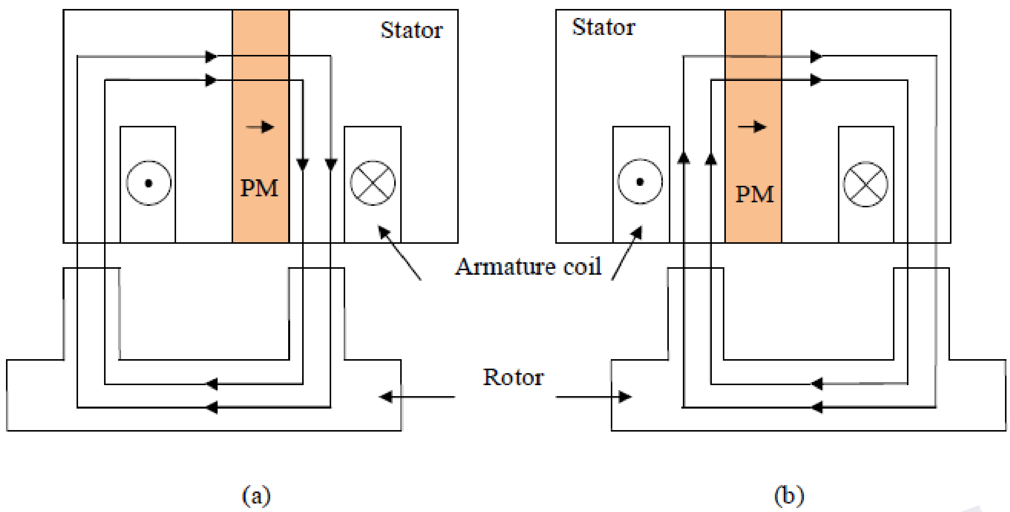

Fig. 2. 3: The principle operation of PMFSM

2.3 Hybrid Excitation Flux Switching Motor (HEFSM)

Hybrid excitation flux switching machines (HEFSMs) are those which utilize primary excitation by PMs as well as DC FEC as a secondary source. Conventionally, PMFSMs can be operated beyond base speed in the flux weakening region by means of controlling the armature winding current. By applying negative d-axis current, the PM flux can be counteracted but with the disadvantage of increase in copper loss and thereby reducing the efficiency, reduced power capability, and also possible irreversible demagnetization of the PMs. Thus, HEFSM is an alternative option where the advantages of both PM machines and DC FEC synchronous machines are combined. As such HEFSMs have the potential to improve flux weakening performance, power and torque density, variable flux capability, and efficiency which havebeen researched extensively over many years [**16**] [**17**] [**18**].

The combinations of stator slots and rotor poles for HEFSMs is illustrated in Fig. 2.4. Fig. 2.4 shows a 6S-4P HEFSM in which the active parts are arranged in three layers in the stator. The inner stator consists of the armature windings, followed by the FECs in the middle layer, while the PMs are placed in outer stator.

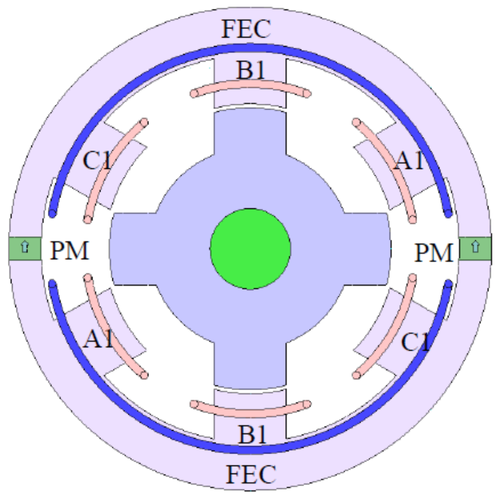

Fig. 2. 4: The example of 6Slot-4Pole HEFSM

The operating principle of HEFSM is illustrated in Fig. 2.5, where the red and blue line indicate the flux from PM and FEC, respectively. In Fig. 2.5(a) and (b), since the direction of both PM and FEC fluxes are in the same polarity, both fluxes are combined and move together into the rotor, hence producing more fluxes with a so called hybrid excitation flux. Furthermore in Fig. 2.5(c) and (d), where the FEC is in reverse polarity, only flux of PM flows into the rotor while the flux of FEC moves around the stator outer yoke which results in less flux excitation. As one benifit of the DC FEC, the flux of PM can easily be controlled with variable flux control capabilities as well as under field weakening and or field strengthening excitation.

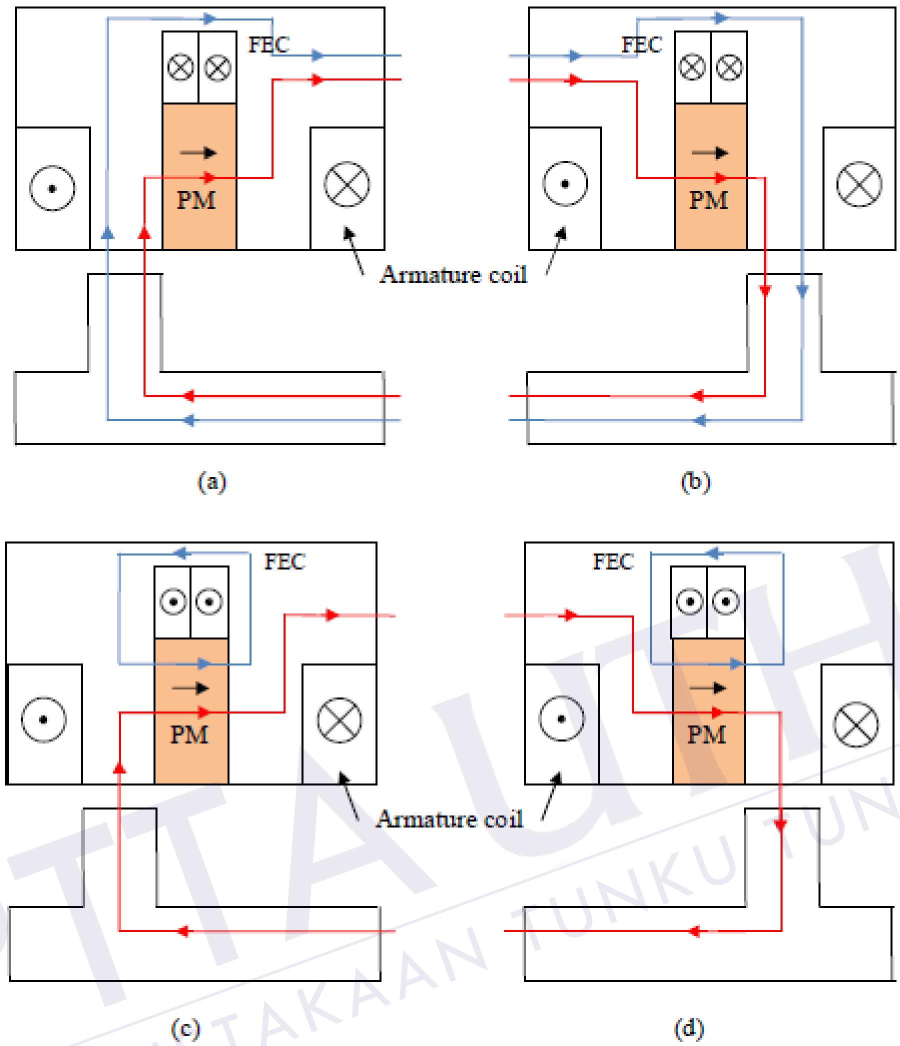

Fig. 2. 5: The operating principle of HEFSM (a) θ*e*=0° - more excitation (b) θ*e*=180° - more excitation (c) θ*e*=0° - less excitation (d) θ*e*=180° - less excitation.

The foregoing HEFSMs having magnets on the stator also suffers from one of three disadvantages.

i. The DC FEC is in series with the field excited by PMs, which limits the flux adjusting capability due to low permeability of the PM
ii. The flux path of DC FEC significantly reduces the main flux excited by magnets and even short circuits the magnet flux
iii. Torque density may be significantly reduced due to less PM volume

REFERENCES

[1] Takashi Kosaka, Nobuyuki Matsui Erwan Sulaiman, "A New Structure of 12Slot-10Pole Field-Excitation Flux Switching Synchronous Machine for Hybrid Electric Vehicles," *Power Electronics and Applications (EPE 2011),Proceedings of the 2011-14th European Conference*, pp. 1-10, 2011.

[2] Fellow IEEE C. C. Chan, "The State of the Art of Electric,Hybrid, and Fuel Cell Vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704-718, 2007.

[3] Fellow IEEE, Yimin Gao, and John M. Miller Mehrdad Ehsani, "Hybrid Electric Vehicles:Architecture and Motor Drives," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 719-728, 2007.

[4] Senior Member IEEE, Chris Mi, Senior Member IEEE, David Wenzhong Gao, "Modeling and Simulation of Electric and Hybrid Vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 729-745, 2007.

[5] K.W. E. Cheng,T.W. Ng,N. C. Cheung X. D. Xue, "Multi-Objective Optimization Design of In-Wheel Switched Reluctance Motors in Electric Vehicles," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 57, no. 9, pp. 2980-2987, 2010.

[6] C. C. Chan,Chunhua Liu, K. T. Chau, "Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 55, no. 6, pp. 2246-2257, 2008.

[7] Chang Sung Jin, and Ju Lee Ki-Chan Kim, "Magnetic Shield Design Between Interior Permanent Magnet Synchronous Motor and Sensor for Hybrid Electric Vehicle," *IEEE TRANSACTIONS ON MAGNETICS*, vol. 45, no. 6, pp. 2835-2838, 2009.

[8] T. Hirose, and N. Matsui T. Kosaka, "Brushless Synchronous Machines with Wound-Field Excitation using SMC Core Designed for HEV Drives," *The 2010 International Power Electronics Conference*, pp. 1794-1800, 2010.

[9] L. J. JOHNSON S. E. RAUCH, "Design Principles of Flux-Switch Altenators," *Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers* , vol. 74, no. 3, pp. 1261-1268, 1955.

[10] Yifan Zhao, Thomas A. Lip0 Bulent Sarlioglu, "A novel doubly salient single phase permanent magnet generator," *Industry Applications Society Annual Meeting, 1994., Conference Record of the 1994 IEEE* , vol. 1, pp. 9-15, 1994.

[11] C. Pollock and M. Wallace, "The flux switching motor, a DC motor without magnets," *Proc. Conf. Rec. IEEE IAS Annual Meeting*, vol. 3, pp. 1980–1987, 1999.

[12] C. Pollock, R. T. Walter, and B. V. Gorti H. Pollock, "Low cost, high power

density,flux switching machines and drives for power tools," *Proc. Conf. Rec. IEEE IAS Annual Meeting*, pp. 1451–1457, 2003.

[13] Design of a three-phase flux reversal machine, "I. Boldea, C. Wang, S. A. Nasar," *Mobile and Personal Satellite Communications Proceedings of the European Workshop on Mobile/Personal Satcoms (EMPS)*, vol. 27, pp. 849-863, 1999.

[14] S. Andersson, I. Boldea, T. J. E. Miller R. P. Deodhar, "The flux reversal machine: A new brushless doubly salient permanent magnet machine," *Proc. Of IEEE-IAS Annual Meeting*, pp. 786-793, 1996.

[15] T. Kosaka, and N. Matsui E. Sulaiman, "Design and Performance of 6-Slot 5-Pole PMFSM with Hybrid Excitation for Hybrid Electric Vehicle Applications," *International Power Electronics Conferences*, pp. 1962-1968, 2010.

[16] L. Vido, M. Gabsi, E. Hoang, M. Lecrivain, and F. Chabot Y. Amara, "Hybrid Excitation Synchronous Machines: Energy Efficient Solution for Vehicle Propulsion," *IEEE Vehicle Power and Propulsion Conference, VPPC 06*, pp. 1-6, 2006.

[17] and Y. Yan C. Zhao, "A review of development of hybrid excitation synchronous machine," *Proc. of the IEEE International Symposium on Industrial Electronics*, vol. 2, pp. 857-862, 2005.

[18] Z.Q. Zhu, and G.W. Jewell R. L. Owen, "Hybrid excited flux-switching permanent magnet machines," *", Proc. 13th European Conf. on Power Electronics and Applications*, pp. 1-10, 2009.

[19] M. F. M. Teridi, Z. A. Husin , M. Z. Ahmad and T. Kosaka E. Sulaiman, "Investigation on Flux Characteristics of Field Excitation Flux Switching Machine with Single FEC Polarity," *Proc. Of The 4th International Conference on Electrical Engineering and Informatics (ICEEI 2013)*, pp. 561-567, 2013.

[20] H. Pollock, and M. Brackley C. Pollock, "Electronically controlled flux switching motors: A comparison with an induction motor driving an axial fan," *Proc. Conf.Rec. IEEE IAS Annual Meeting*, pp. 2465–2470, 2003.

[21] J. F. Bangura, "Design of high-power density and relatively high efficiency flux switching motor," *IEEE Trans. Energy Convers*, vol. 21, no. 2, pp. 416–424, 2006.

[22] Mecrow B, Armstrong A Zulu A, "A wound-field three-phase flux-switching synchronous motor with all excitation sources on the stator," *IEEE Trans. Ind. Appl*, vol. 46, pp. 2363-2371, 2010.

[23] N. Matsui and M. Z. Ahmad E. SulaimanT. Kosaka, "Design Improvement and Performance Analysis of 12Slot-10Pole Permanent Magnet Flux Switching Machine with Field Excitation Coils," *Proc of The 5th International Power Engineering and Optimization Conference (PEOCO2011)*, pp. 202-207, 2011.